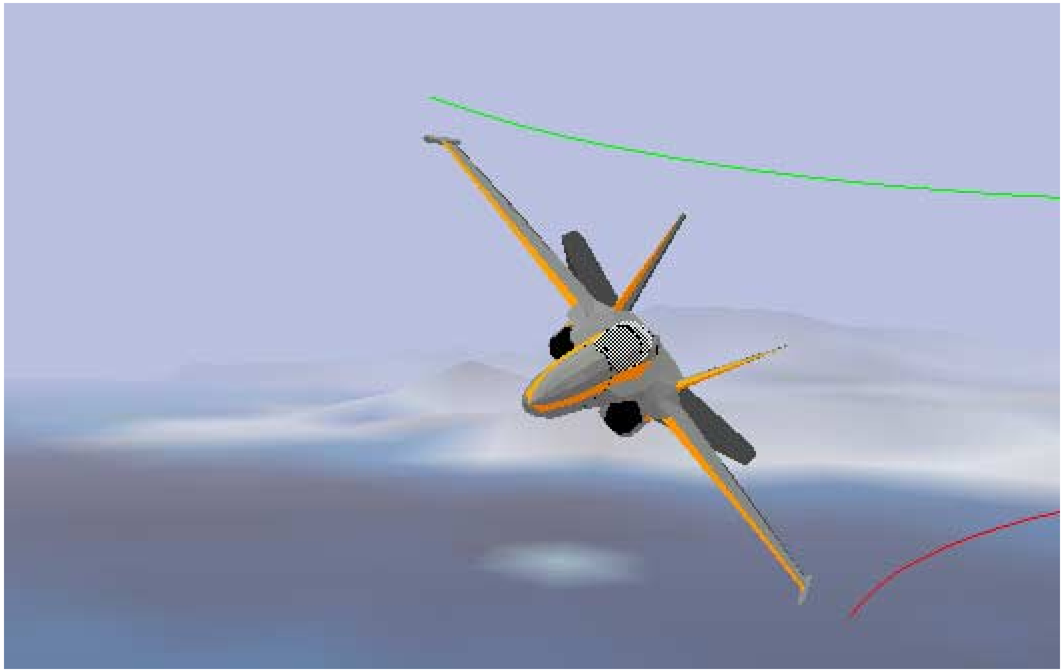
UAV Control and Simulation



Princeton University

FAA/NASA Joint University Program

Quarterly Review - October, 2000

Outline

- Introduction
- A rule-based controller simulation
  - Rule-based scheduler presentation
  - Simulation architecture
  - Simulation results
- Control law for nonlinear UAV model
  - Nonlinear model
  - Trajectory tracking
  - Barrel roll test
- Concluding remarks

New UAV* Requirements

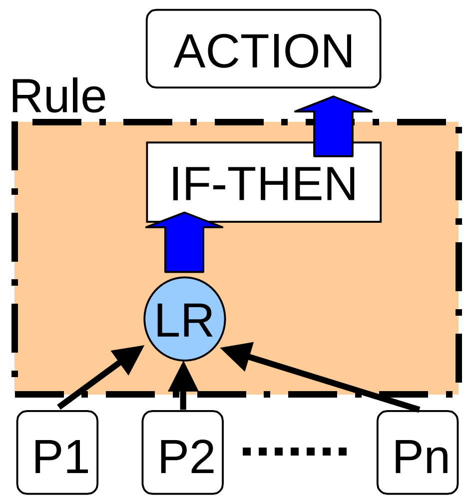
- Foreseen UAV applications
  - Unmanned Combat Air Vehicles
    - (Boeing / Lockheed Martin) [1]
  - Wireless communications relay
    - (Proteus - Scaled Composites) [2]
  - Meteorological probing
    - (Aerosonde) [3]

- Requirements
  - Long and/or dangerous missions
  - Team approach for increased reliability
    - Aircraft failure accommodation (task redistribution over remaining vehicles)
    - Concerted action (fly different paths for mutual support)

*Unmanned Air Vehicles

Rule-based Scheduler Presentation

- Rule base paradigm
  ⇒ Production rules applied to a database storing the parameters by matching premises

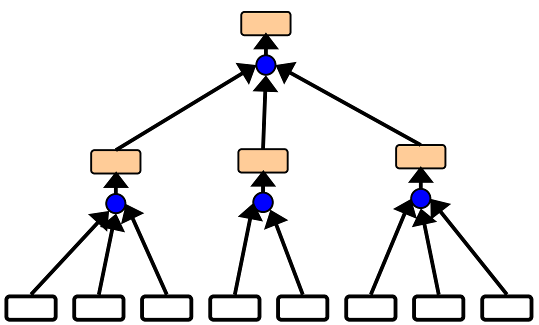


LR: Logical Relation (AND,OR)

P1,…,Pn: Premises 1 to n

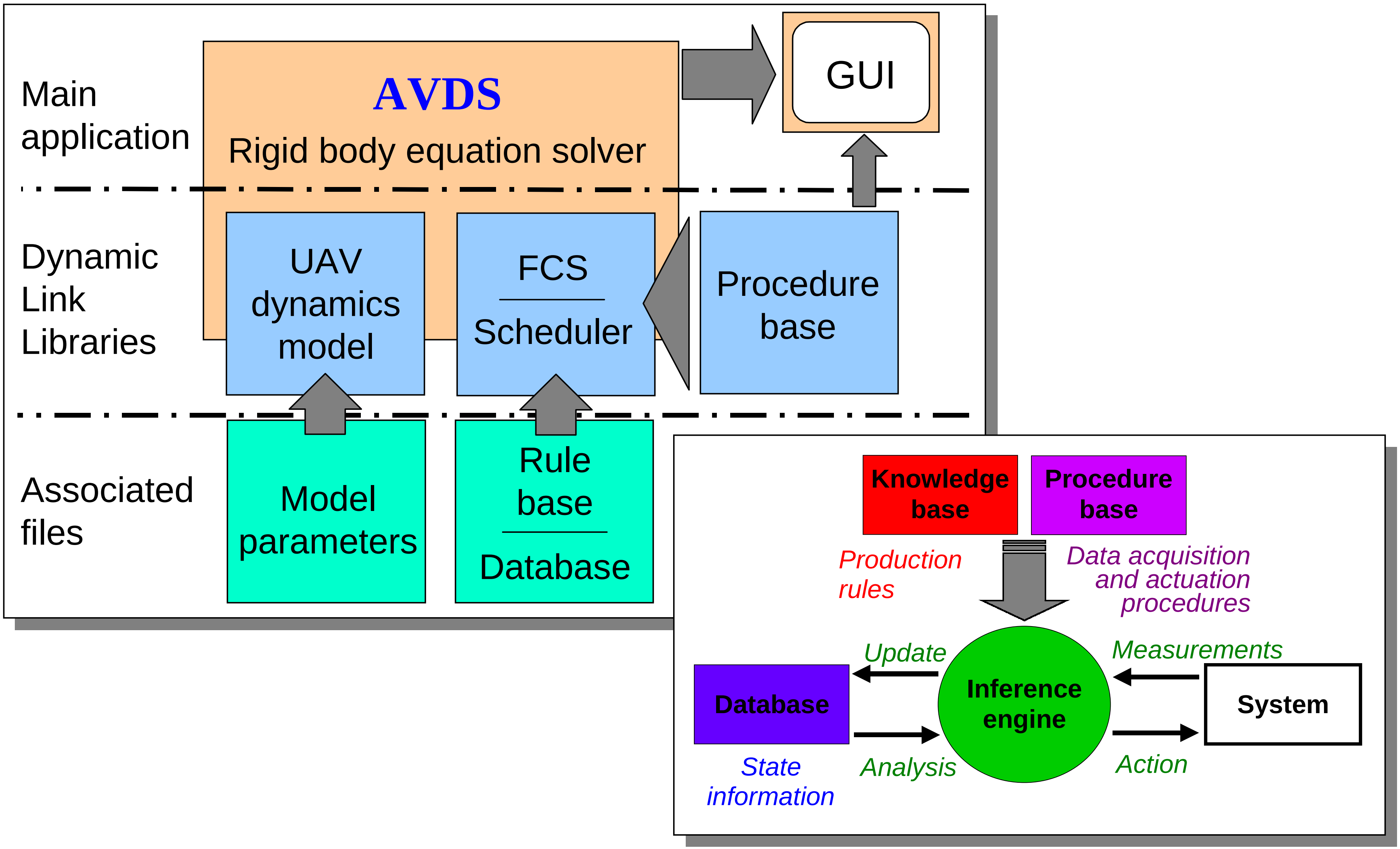
Action and Premises are either parameters or procedures returning a value.

- Rule-based scheduler
  - 1 to 1 relation between actions and rules
  - Hierarchical structure of rules

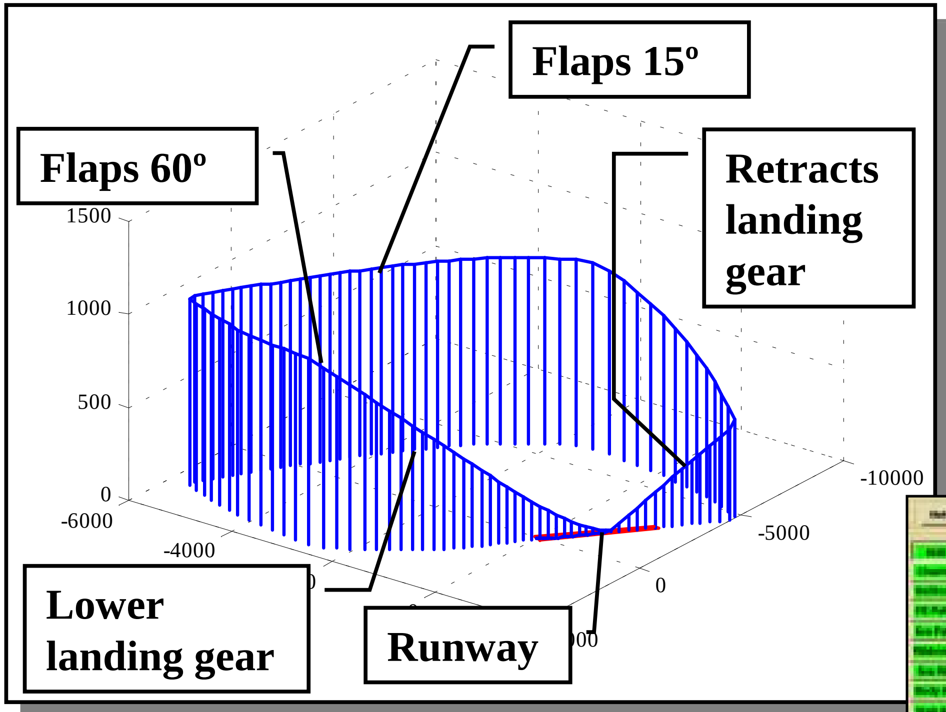


  - Uses THEN or SYNC as logical relations between tasks
  - Leaves of the tree are procedures representing subtasks while the root is the main task.
  - Parameters take values:
    “Done”, “Not Done”

Simulation Architecture



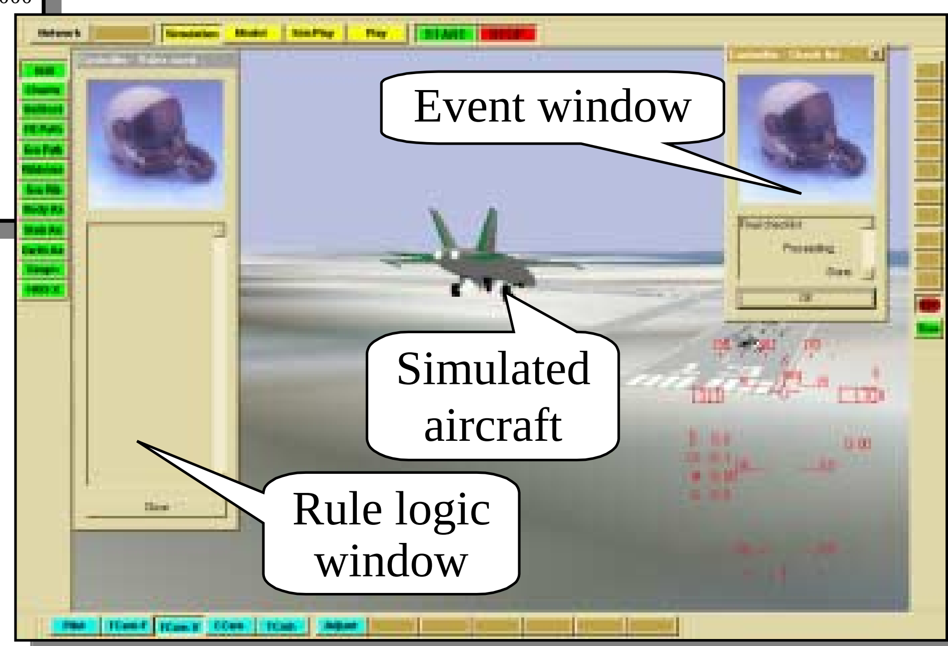
Simulation Results



- Airport traffic pattern flight simulation
  - Aircraft configuration
  - Waypoints sequence

  managed by the rule-base scheduler

- Simulation visual interface
  - Tools are provided for the user to follow the rule-based logic
  - Tools for user interaction with the simulation are under development



UAV Nonlinear Model

- Assumptions
  - Three time differentiable trajectory specified in earth coordinates, $\mathbf{x}_{\mathbf{e}}(t)$
  - No sideslip
- Notations

  e - earth frame

  b - body frame

  w - wind frame

  $\mathbf{H}_1^2$ - transformation from frame 1 to frame 2

  $\mathbf{I}$ - inertia matrix

- Dynamics equations

$$(1)\begin{cases} \ddot{\mathbf{x}}_{\mathbf{e}} = \mathbf{g} + \mathbf{H}_{\mathbf{w}}^{\mathbf{e}} \mathbf{f}_w \\ \dot{\mathbf{H}}_{\mathbf{w}}^{\mathbf{e}} = \mathbf{H}_{\mathbf{w}}^{\mathbf{E}} \hat{\omega}_{\mathbf{w}} \end{cases}$$

$$(2)\begin{cases} \mathbf{f}_{\mathbf{w}} = \mathbf{f}_{\mathbf{w}}(\alpha, \beta, T) \\ \dot{\omega}_{\mathbf{b}} = \mathbf{I}^{-1}\left[\mathbf{m}_{\mathbf{b}} - \omega_{\mathbf{b}} \times \mathbf{I}\omega_{\mathbf{b}}\right] \\ \omega_{\mathbf{b}} = \mathbf{H}_{\mathbf{w}}^{\mathbf{b}}(\alpha, \beta)\omega_{\mathbf{w}} \end{cases}$$

See J. Hauser et al.,

"Aggressive Flight Maneuvers"

Trajectory Tracking

- State feedback linearization
  - Desired trajectory third derivative:

$$\dddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} = \mathbf{H}_{\mathbf{w}}^{\mathbf{e}} \begin{bmatrix} \omega_{w2} f_{w3} \\ \omega_{w3} f_{w1} \\ -\omega_{w2} f_{w1} \end{bmatrix} + \mathbf{H}_{\mathbf{w}}^{\mathbf{e}} \begin{bmatrix} \dot{f}_{w1} \\ -f_{w3}\omega_{w1} \\ \dot{f}_{w3} \end{bmatrix}$$

  - Linearizing control law:

$$\begin{bmatrix} f_{w1} \\ -f_{w3}\omega_{w1} \\ f_{w3} \end{bmatrix} = \begin{bmatrix} -\omega_{w2} f_{w3} \\ \omega_{w3} f_{w1} / f_{w3} \\ \omega_{w2} f_{w1} \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1/f_{w3} & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{H}_{\mathbf{w}}^{\mathbf{e}\,\mathrm{T}} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}$$

$$\mathbf{u} = \dddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} + k_2(\ddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} - \ddot{\mathbf{x}}_{\mathbf{e}}) + k_1(\dot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} - \dot{\mathbf{x}}_{\mathbf{e}}) + k_0(\mathbf{x}_{\mathbf{e}}^{\mathbf{d}} - \mathbf{x}_{\mathbf{e}})$$

- Nonlinear dynamic inversion

$$\dot{\omega}_{\mathbf{b}} = K(\omega_{\mathbf{b}}^{\mathbf{d}} - \omega_{\mathbf{b}})$$

$$= K \begin{bmatrix} 1 & 0 & \sin\alpha \\ 0 & 1 & 0 \\ 0 & 0 & \cos\alpha \end{bmatrix} \begin{bmatrix} \omega_{w1} \\ -2m\dot{f}_{w3} / (\rho S V^2 C_{L\alpha}) \\ 2m\dot{f}_{w2} / (\rho S V^2 C_{Y\beta}) \end{bmatrix}$$

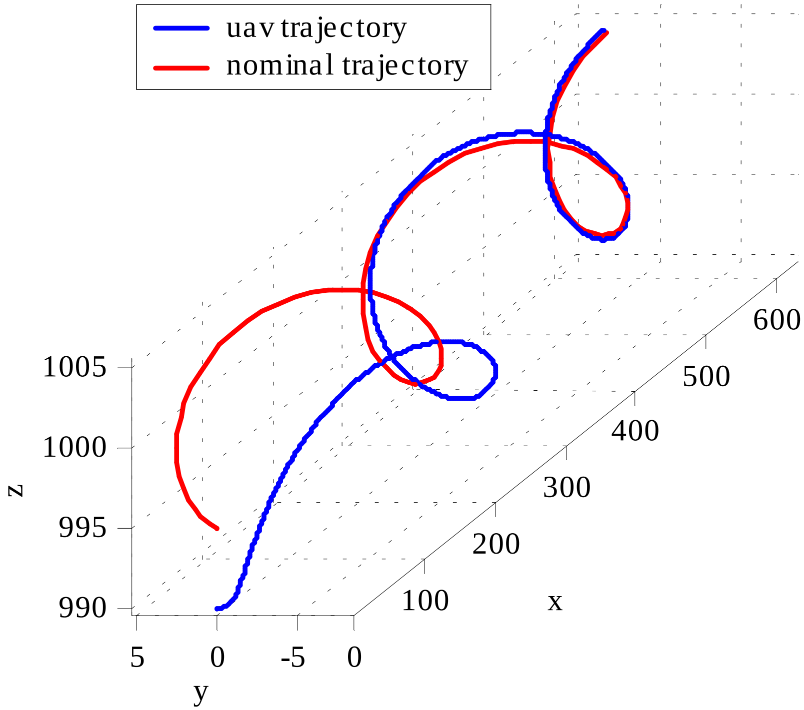
$$\mathbf{m}_{\mathbf{b}} = \mathbf{I}\dot{\omega}_{\mathbf{b}} + \omega_{\mathbf{b}} \times \mathbf{I}\omega_{\mathbf{b}}$$

$$\dot{f}_{w2} = -k_\beta f_{w2}$$

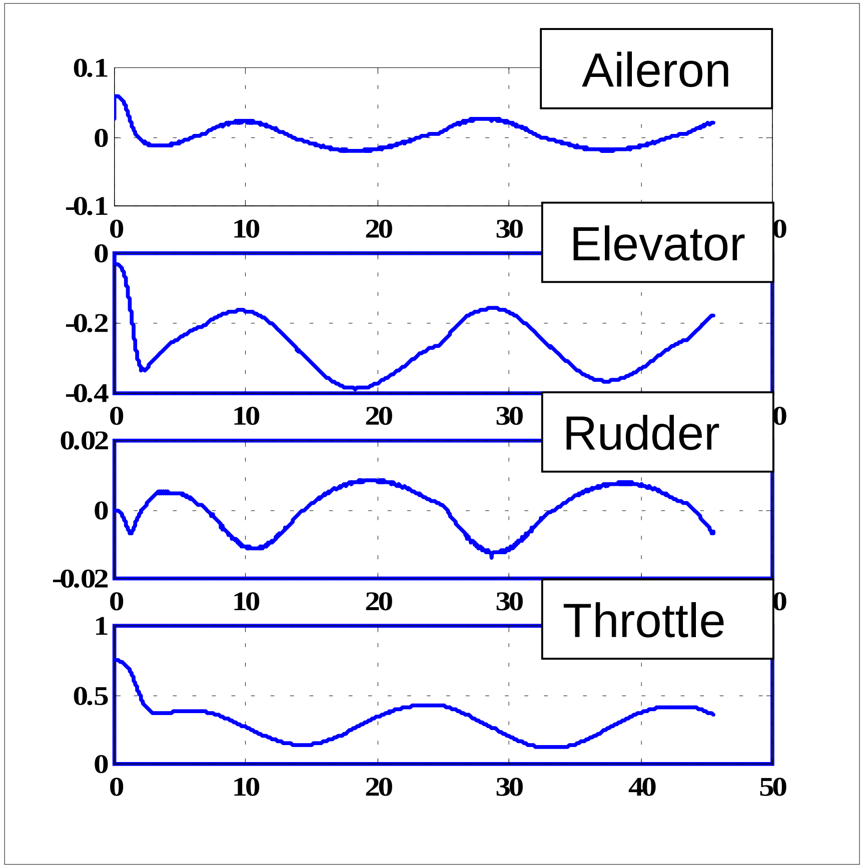
$$T = T(\alpha, f_{w1})$$

Barrel roll test

- 3D view of the UAV trajectory



- Control inputs used



Concluding Remarks

- Tools at our disposal:
  - A control law to track trajectories specified in earth coordinates.
  - A controller structure capable of logical reasoning.

- Future work:
  - Set up a multi-aircraft simulation.
  - Use rule-based control to coordinate them.